DTIC FILE COPY

HDL-SR-89-4

December 1989

Transistor and Solid-State Technology: A Historical Development

by Kelly W. Bennett

AD-A218 141

U.S. Army Laboratory Command
Harry Diamond Laboratories
Adelphi, MD 20783-1197

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1a. REPORT SECURITY CLASSIFICATION: Unclassified

1b. RESTRICTIVE MARKINGS

2a. SECURITY CLASSIFICATION AUTHORITY

2b. DECLASSIFICATION/DOWNGRADING SCHEDULE

3. DISTRIBUTION/AVAILABILITY OF REPORT: Approved for public release; distribution unlimited.

4. PERFORMING ORGANIZATION REPORT NUMBER(S): HDL-SR-89-4

5. MONITORING ORGANIZATION REPORT NUMBER(S)

6a. NAME OF PERFORMING ORGANIZATION: Harry Diamond Laboratories

6b. OFFICE SYMBOL (if applicable): SLCHD-NW-RP

7a. NAME OF MONITORING ORGANIZATION

6c. ADDRESS (City, State, and ZIP Code): 2800 Powder Mill Road, Adelphi, MD 20783-1197

7b. ADDRESS (City, State, and ZIP Code)

8a. NAME OF FUNDING/SPONSORING ORGANIZATION: Defense Logistics Agency/AMC

7b. OFFICE SYMBOL (if applicable)

9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER

8c. ADDRESS (City, State, and ZIP Code): 5001 Eisenhower Ave, Alexandria, VA 22333-0001

10. SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT ACCESSION NO.
6.00.00.S			

11. TITLE (Include Security Classification): Transistor and Solid-State Technology: A Historical Development

12. PERSONAL AUTHOR(S): Kelly W. Bennett

13a. TYPE OF REPORT: Final

13b. TIME COVERED: FROM 3/7/88 TO 3/25/88

14. DATE OF REPORT (Year, Month, Day): December 1989

15. PAGE COUNT: 15

16. SUPPLEMENTARY NOTATION: HDL project: 225823

17. COSATI CODES

FIELD	GROUP	SUB-GROUP
09	01	
09	03	

18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number): Transistor, solid-state technology, transistor history, solid-state ~~history~~, semiconductor, integrated circuit ~~history~~, IC classification, transistor miniaturization, semiconductor technological advances. (RH)

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

From the invention of the first transistor in 1947 to solid-state advances leading up to the 21st century, this paper presents the historical developments of solid-state devices. Along with individual solid-state milestones, the paper relates the solid-state accomplishments to advances in the computer industry, military, and the commercial world.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT: ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS

21. ABSTRACT SECURITY CLASSIFICATION: Unclassified

22a. NAME OF RESPONSIBLE INDIVIDUAL: Kelly W. Bennett

22b. TELEPHONE (Include Area Code): (202) 394-3190

22c. OFFICE SYMBOL: SLCHD-NW-RP

DD Form 1473, JUN 86 *Previous editions are obsolete.*

SECURITY CLASSIFICATION OF THIS PAGE
UNCLASSIFIED

Contents

Tables

Introduction

Over the past 20 years an average 20-percent improvement a year in the cost-to-performance ratio of electronic products has been achieved by continuous advances in semiconductor electronics [1]. This amazing growth in performance is due mostly to transistor miniaturization. Because of integrated circuit (IC or chip) developments in transistor miniaturization, over a million transistors can be packed in an IC no bigger than your fingernail.

To fully appreciate the advances in transistor technology, one needs only to look at the computer industry as an example. In the past 33 years, computer power has increased dramatically. In 1955, a mainframe computer took more than 6 minutes at a cost of $14.54 to perform 1700 typical data-processing operations. By contrast, today's computers can perform the same operations in half a second at a cost of only 4¢ [1].

Transistor miniaturization has inspired a new era in electronics: the age of microelectronics. From its basic beginning to its present complex form, the transistor has affected the world in tremendous ways.

Transistors: Precursor to Integrated Circuitry

The beginning of the semiconductor electronics world as we know it today began back in 1947 with the development of the first transistor. In late 1947, two scientists working at Bell Laboratories, Bardeen and Brattain, invented the point contact transistor. Using two gold wires pressed into a germanium base, Bardeen and Brattain discovered a voltage output (with respect to the germanium base) at the collector which was greater than the input to the emitter. Although these first transistors were not very good, they signaled the birth of the solid-state amplifier. At that time, neither scientist knew that their discovery would cause the vacuum tube to become virtually obsolete in less than 25 years.

Following the discovery of the point-contact transistor in 1947 was an era of rapid discovery in transistor electronics, extending through 1960. Between 1947 and 1960, a series of inventions quickly brought transistor electronics from early childhood to full development. Table 1 shows the significant milestones of transistor electronics during this period.

Although these advances were extremely significant, the microelectronics age did not truly begin until the development of circuit integration techniques. Nevertheless, the advances in transistor electronics of the 1950's launched the world into the age of digital wristwatches, pocket calculators, microcomputers, and microprocessor-based military systems.

Table 1. Technological milestones in discrete transistors: 1947–1960

Date	Milestone description
1947	Invention of **point-contact transistor** by Bardeen and Brattian.
1950	Ability developed to grow ultrapure **single-crystal germanium** with less than 1 part per billion of impurity atoms.
1951	**Junction transistors** formed by introduction of impurities called donor or acceptor atoms in the range of 1 part per 100 million.
1951	**Junction field-effect transistor** (JFET) developed, a field-effect transistor which has an electric field applied to the channel through a P-N diode.
1952	Development of **zone melting and refining**, a process which produces chemically purified polycrystalline silicon material for single-crystal ingot growth.
1952	Development of the **single-crystal silicon** process, which converts the purified polycrystalline silicon material into monocrystalline silicon cylinders (ingots) for wafer creation.
1953	Development of **surface-barrier transistor**, a transistor made on a semiconductor wafer where etched contacts have been made for the emitter and collector-base junctions. The substrate is the base.
1954	Development of **oxide masking:** silicon forms a stable oxide when exposed to oxidizing agents at high temperature.This oxide (silicon dioxide, SiO_2) acts as a protective mask for the purpose of inserting impurities by diffusion or ion implantation into selected areas of the wafer which has been stripped of oxide.
1954	First production-level **silicon-junction transistors** made for commercial use.
1955	**Diffused-base transistor** developed, a type of transistor made by combining diffusion and alloy techniques [2].
1959	**Planar transistor** developed—a diffused transistor in which the emitter, base, and collector regions terminate in the same plane surface. In general, semiconductor devices which terminate in the same plane surface define a planar process. Part of the planar process is the use of silicon dioxide for protecting the P-N junctions, masking, and passivating. In the present fabrication of integrated circuits, the planar process is still the basic process [2].
1959	**IBM 7090/7094 series computers** appear—first computer built using discrete transistors as opposed to vacuum tubes.
1960	Development of **epitaxial transistor**, a transistor fabricated with one or more epitaxial layers. An epitaxial layer is a grown or deposited crystal layer with the same crystal orientation as the original material. For semiconductors, the epitaxial material is the same as the substrate material. For silicon wafers, the epitaxial material is monocrystalline silicon [2].
1960	Development of the **MOSFET** (metal-oxide-semiconductor field-effect transistor),which has a metal or polysilicon gate electrode separated by an oxide layer from the semiconductor channel. An electric field affects the channel, if an external potential is applied between the gate and substrate.
1960	Development of **Schottky barrier diode**, a metal-semiconductor diode with a rectifying contact. This results in a diode with volt-ampere characteristics very close to P-N diodes. Because of manufacturing problems, commercial Schottky-barrier diodes were not available until the late 1960's.

Integrated Circuit Development

The Beginnings of the IC

The development of the semiconductor IC was foreseen in 1952 by G.W.A. Drummer of the Royal Radar Establishment in Great Britain. Addressing the Electronics Components Conference, Drummer said, "With the advent of the transistor and the work in semiconductors generally, it seems now possible to envisage electronics equipment in a solid block with no connecting wires. The block may consist of layers of insulating, conducting, rectifying, and amplifying materials, the electric functions being connected directly by cutting out areas of the various layers" [3].

Drummer's dream came true in 1958 with the development of the first monolithic IC, an entire circuit built out of silicon. These first monolithic IC's were phase oscillators using a distributed-RC network and a flip-flop. The total elapsed time from conception to finished working silicon integrated circuit (SIC) was less than 3 months.

Although *an amazing* accomplishment, the SIC was not an immediate success in the commercial business arena. Much of the dissatisfaction with the SIC came from the system and circuit design world. Users (system and circuit designers) had to learn how to work with the new technology. With the steady evolution of the IC from 1959 to 1972, users' acceptance and familiarity increased. Important milestones of this period are shown in table 2.

A major influence in the acceptance of SIC technology was the production of logic gates as part of a logic family, i.e., resistor-transistor logic (RTL), diode-transistor logic (DTL), transistor-transistor logic (TTL), etc. This enabled circuit and system designers to use basic logic gates to design their custom circuits, boards, and systems, as opposed to using discrete transistors. The design problem of circuit and system compatibility was solved through the use of IC's from the same logic family. At the same time, the logic families allowed IC manufacturers to produce cost-effective IC's.

Table 2. Technological milestones in integrated circuitry: 1959–1975

Date	Milestone description
1959	Development of **planar SIC**, a silicon integrated circuit made by the planar process, using reverse-biased p-n junctions to isolate the devices and a metal layer level for electrical connection.
1961	The first **commercial monolithic IC**, part of the digital logic family known as **RTL** (resistor-transistor logic). RTL gates use a resistor connected to the base input of a NPN transistor.
1962	Development of **diode-transistor logic (DTL)** family. DTL gates use diodes as the input of the logic gate to control the transistor output.
1962	Development of **transistor-transistor logic (TTL)** family. TTL uses multiple emitters of an input transistor as the input of the logic gate. This input is used to control the collector output of the output transistor.
1962	Development of **emitter-coupled logic (ECL)** family, a digital logic family based on a difference amplifier (DIFF AMP) configuration. The output voltage of the DIFF AMP is proportional to the difference between the two input voltages, V_a and V_b, where one input voltage acts as a reference voltage. For example, let $V_b = V_{ref}$. If $V_a - V_{ref}$ is less than zero by at least 0.1 V, then the output of the transistor with the input voltage, V_{ref}, will be a constant negative voltage called $V(0)$ (low), or corresponding to a binary zero. Conversely, if $V_a - V_{ref}$ is greater than zero by at least 0.1 V, then the output voltage is a constant positive voltage called $V(1)$ (high), or corresponding to a binary one.
1962	Development of **MOS IC**, a monolithic integrated circuit consisting of MOS devices as opposed to bipolar.
1963	Development of technique called **complementary MOS (CMOS)**, the design and fabrication of devices by interconnecting both PMOS and NMOS transistors together. An example is the interconnection of the gate input of a PMOS transistor with the gate input of a NMOS transistor to form a CMOS inverter.
1964	First **linear integrated circuits** developed; these are monolithic IC's which have amplifying circuits on them such that the output is an amplified version of the input and is not digital.
1965	**IBM System 360 series** built, the first computer using integrated circuits as opposed to discrete transistors.
1968	Development of **MOS memory chips**—MOS IC's having a transistor configuration capable of storing digital data.
1969	Development of the **charge-coupled device (CCD)**; this is an MOS transistor with an extremely long channel with several gates (maybe as many as 1000 gates) closely spaced between the source and drain. By applying the proper gate potential in the proper sequence, charge can be transferred from one gate to the next gate. The use of CCD's is a cost-efficient way to make shift registers and serial memories. CCD's are also called CTD's (charge-transfer devices) [4].
1970	Development of **MOS calculator chips**, MOS IC's which perform specialized arithmetic functions such as adding, subtracting, multiplying, and dividing.
1971	Development of the **microprocessor**, a digital computer on one or more chips that is customized by the user via software.
1972	Development of a digital logic family known as **I^2L** (integrated injection logic). This logic family uses normal bipolar-junction transistors in a new circuit configuration to form new logic gates. These new logic gates require low power, are extremely fast, and allow packing densities which approach MOS technology.

As IC technology developed, the number of components that could be put on a chip increased, leading to another method of categorizing chips: the level of integration. Table 3 indicates the increase in component count (transistor, diode, resistor, or capacitor) per IC chip over the years.

The Present Age: Memory and Microprocessor Development

With the coming of large-scale and very-large scale integration (LSI and VLSI), the 1970's brought us semiconductor memories, microcomputer chips, and large mainframe computers with all-semiconductor main memory. In 1970, Intel and Fairchild introduced 1000-bit commercial RAM's (random access memories) into the marketplace. A year later, the first computer with all-semiconductor main memory, the IBM system 370/145, was introduced. Initially, the IBM 370/145 contained 128-bit IC chips and offered up to 512 kilobytes of memory. By comparison, a state-of-the-art experimental 4-megabit RAM chip holds as much information as did the entire main memory of the 370/145 [1]. By the middle of the 1970's, 16-kilobit RAM's were commonplace, and 64-kilobit RAM's became available in 1979.

One of the most significant microelectronic discoveries of the decade occurred in 1977 with the invention of the microcomputer on a chip. The microcomputer on a chip is an IC consisting of all the basic components of a computer (clock, read-only memory (ROM), microprocessor (CPU), RAM, and input/output (I/O) devices). An example of the microcomputer on a chip is the Intel 8748 microcomputer consisting of 20,000 transistors,

Table 3. Milestones in miniaturization: 1951–1975 [4]

Date	Milestone	Components per chip
1951	Discrete transistors	
1960	Small-scale integration (SSI)	Less than 100 components per chip
1966	Medium-scale integration (MSI)	More than 100 but less than 1,000 components per chip
1969	Large-scale integration (LSI)	More than 1,000 but less than 10,000 components per chip
1975	Very-large-scale integration (VLSI)	More than 10,000 components per chip

measuring 5.6 × 6.6 mm, and costing only $250 in 1978. By comparison, an Intel 8748 microcomputer chip is 20 times faster than the 1946 ENIAC computer, has more memory, uses far less power, is thousands of times more reliable, and costs 0.0001 as much as an ENIAC [4,5].

Just as the early 1970's brought us complex chips able to store several hundred bits of information, the early to middle 1980's brought us higher density IC's with even greater complexity. Present-day semiconductor memories can store up to a million or more bits of information. With such emphasis on miniaturization, the entire semiconductor industry is working toward geometric dimensions approaching the atomic level. As the semiconductor industry demands smaller devices, equipment manufacturers will have to develop more complex machines to handle the smaller geometry. Additionally, the scientific community will have to delve deeper into understanding the basic underlying principles of semiconductor materials, devices, and processes [1].

The Future of Integrated Circuitry

For the next 20 years, technology will be emphasizing greater speed and circuit density through significant decrease in the physical size of the bit. As accurately as one can predict, technology will have advanced to several million transistors on a single FET microprocessor chip by the early 1990's, and beyond that, single-chip CPU's which operate at several tens of MIPS (millions of instructions per second) [1].

Conclusion: The IC in Society

What started a little over 40 years ago as the beginning of the transistor age has no end in sight, but only continual progress, where the state of the art is redefined every 18 months. Invention gave way to revolution without parallel. This revolution can be seen every day in our society. In today's world, microelectronic applications can be seen in automobiles, home computers, stereo equipment, communication devices, and many other areas. From a military standpoint, today's weapon systems use microelectronic devices in virtually every facet of their design. Defense applications using microelectronics include nuclear, high-power microwave, and anti-radiation missile/countermeasure systems; fuzing and self-contained munitions; signal and information processing equipment; radar; and many other military areas. As microelectronic devices become smaller and more powerful, many new applications in many new fields will be developed. As with the ever-increasing use of microelectronics in society, there is no end in sight to the improvement and progress of microelectronics.

Acknowledgements

I thank Edward Nader of Defense Logistics Agency and Robert B. Reams of Harry Diamond Laboratories for support of this project. I would like to thank Chris Lewis, Ted Blomquist, Robert B. Reams, and Bohdan J. Dobriansky for their comments and reviewing of this paper. The help of all others involved in this work is appreciated.

References

1. John A. Armstrong, *Solid State Technology and the Computer; 10 Years Later, Small is Still Beautiful*, Solid State Technology **30** (12):80–83 (December 1987).

2. Rudolf F. Graf, *Modern Dictionary of Electronics*, Indiana: Howard W. Sams & Co., 1968.

3. Arthur B. Glaser and Gerald E. Subak-Sharpe, *Integrated Circuit Engineering*, Massachusetts: Addison-Wesley Publishing Company (1977).

4. Jacob Millman, *Microelectronics: Digital and Analog Circuits and Systems*, New York: McGraw-Hill Book Company (1979).

5. Roy A. Colclaser, *Microelectronics: Processing and Device Design*, New York: John Wiley & Sons, 1980.

DISTRIBUTION

ADMINISTRATOR
DEFENSE TECHNICAL INFORMATION CENTER
ATTN DTIC-DDA (12 COPIES)
CAMERON STATION, BUILDING 5
ALEXANDRIA, VA 22304-6145

US ARMY MATERIEL COMMAND
ATTN E. NADER, AMCPD-PT
5001 EISENHOWER AVENUE
ALEXANDRIA, VA 22333

BOOZ ALLEN & HAMILTON, INC
ATTN J. TERRELL (2 COPIES)
4330 EAST WEST HIGHWAY
BETHESDA, MD 20814

US ARMY LABORATORY COMMAND
ATTN TECHNICAL DIRECTOR, AMSLC

INSTALLATION SUPPORT ACTIVITY
ATTN LEGAL OFFICE, SLCIS-CC

USAISC
ATTN TECHNICAL REPORTS BRANCH,
AMSLC-IM-TR (2 COPIES)

HARRY DIAMOND LABORATORIES
ATTN D/DIVISION DIRECTORS
ATTN LIBRARY, SLCHD-TL (3 COPIES)
ATTN LIBRARY, SLCHD-TL (WOODBRIDGE)
ATTN CHIEF, SLCHD-NW-CS
ATTN CHIEF, SLCHD-NW-E
ATTN CHIEF, SLCHD-NW-EH
ATTN CHIEF, SLCHD-NW-EP
ATTN CHIEF, SLCHD-NW-ES
ATTN CHIEF, SLCHD-NW-P
ATTN CHIEF, SLCHD-NW-R
ATTN CHIEF, SLCHD-NW-RP

HARRY DIAMOND LABORATORIES
(cont'd)
ATTN CHIEF, SLCHD-NW-RS
ATTN CHIEF, SLCHD-NW-TN
ATTN CHIEF, SLCHD-NW-TS
ATTN W. VAULT, SLCHD-NW
ATTN L. J. JASPER, JR., SLCHD-NW-CS
ATTN B. LUU, SLCHD-NW-EP
ATTN R. D. HOPKINS, SLCHD-NW-P
ATTN J. M. BENEDETTO, SLCHD-NW-RP
ATTN T. V. BLOMQUIST, SLCHD-NW-RP
ATTN H. E. BOESCH, JR, SLCHD-NW-RP
ATTN W. M. DeLANCEY, SLCHD-NW-RP
ATTN B. R. GEIL, SLCHD-NW-RP
ATTN T. GRIFFIN, SLCHD-NW-RP
ATTN A. J. LELIS, SLCHD-NW-RP
ATTN J. McCULLEN, SLCHD-NW-RP
ATTN F. B. McLEAN, SLCHD-NW-RP
ATTN T. J. MERMAGEN, SLCHD-NW-RP
ATTN T. R. OLDHAM, SLCHD-NW-RP
ATTN R. B. REAMS, SLCHD-NW-RP
ATTN B. J. ROD, SLCHD-NW-RP
ATTN T. L. TAYLOR, SLCHD-NW-RP
ATTN F. J. AGEE, SLCHD-NW-RS (3 COPIES)
ATTN H. A. EISEN, SLCHD-NW-TS
ATTN M. S. BINSELL, SLCHD-PO-P
ATTN G. C. GILLESPIE, SLCHD-PO-P
ATTN J. BRUNO, SLCHD-ST-AP
ATTN J. T. PHAM, SLCHD-ST-AP
ATTN M. S. TOBIN, SLCHD-ST-AP
ATTN C. ARSEM, SLCHD-ST-SA
ATTN J. COSTANZA, SLCHD-ST-SA
ATTN M. WRENN, SLCHD-ST-SA
ATTN J. DeHART, SLCHD-TA-SE
ATTN R. HARRELL, SLCHD-TA-SE
ATTN L. KITCHMAN, SLCHD-TA-SE
ATTN D. THIER, SLCHD-TA-SE
ATTN K. W. BENNETT, SLCHD-NW-RP (50 COPIES)